MICROWAVE KICKERS AND PICKUPS

C.S.Taylor
CERN, Geneva, Switzerland

ABSTRACT
This paper describes the pickups and kickers used for diagnostics and feedback control circuits in particle accelerators at frequencies above a GigaHerz. The purposes and technical properties required of these elements in an accelerator environment are outlined, and the various types of pickups and kickers which have been developed to meet these requirements are described.

1. INTRODUCTION

Pickups are used in accelerators to detect some property of a particle beam, either for direct diagnostic purposes, or, in conjunction with a kicker, in a closed feedback loop to correct or modify the beam properties. When either the diagnostic measurement or feedback loop requires fine time resolution one is led to the wider frequency bandwidths of the microwave region, above say 1 GHz, where the components contain sections of distributed constants rather than the lumped constants of lower frequencies.

The beam properties in which one is most interested include the beam intensity and position, and refinements of these properties such as the particle distributions with frequency or momentum in the longitudinal and transverse directions. This information can be used diagnostically to study the effects of the accelerating machine parameters on the particle motion, or it can be amplified and fed to a kicker, to modify the incoherent particle amplitudes by feedback as in stochastic cooling, requiring large bandwidths, or to use the same circuit for the measurement of beam transfer functions, or at lower frequencies to control and damp coherent beam motion or ion oscillations by feedback.

We are mainly concerned here with pickups and kickers for protons and antiprotons, but some reference is made to the devices used for electron or positron beams.

2. GENERAL DESCRIPTIONS

A beam of charged particles passing along an evacuated tube in an accelerator or beam line can be detected as an image current flowing along the metal wall, by a transformer secondary wound around the tube, by a resistive gap pickup, by loops at the wall acting as directional couplers and linking with the fields accompanying the beam current flow, by capacitive coupling of beam electric field to plates in the beam proximity, by direct excitation of a resonant cavity by a beam along the axis, by a wall array of slots which couple the electromagnetic wave motion accompanying the beam to a transmission line, or by a dielectric slab or corrugated wall waveguide, which achieves the same thing, and etc. These latter structures which couple the particle fields to a single transmission line have come to be known as travelling wave structures.

In general these mechanisms can be reversed to produce a kicker action on the beam.

Of these methods, those which have been developed for the GHz regions are resistive gap pickups, directional couplers, cavities and travelling wave structures.

Before discussing the microwave structures in more detail we need to define the technical requirements of pickups and kickers in general.

3. QUALITY FACTORS AND TECHNICAL REQUIREMENTS

3.1 Transfer impedance and kicker constant

A prime criterion for a pickup is its sensitivity, or the signal voltage produced at the output terminals for a given beam current. This quantity has the dimensions of impedance and so is expressed as the *transfer impedance* or *sensitivity* in ohms [1, 2]. (Since the pickup takes up valuable straight-section length in an accelerator one needs to know as well the transfer impedance per meter of pickup tank.)

For a longitudinal pickup, the transfer impedance is

$$Z_{\parallel} = \frac{V_p}{I_b} \tag{1}$$

where V_p is the output voltage and I_b is the beam current, and for a pickup for transverse motion

$$Z_{\perp} = \frac{V_p}{I_b \delta} \tag{2}$$

where δ is the transverse displacement in mm.

The criterion for a kicker is the *kicker constant,* the complex ratio of energy change ΔE in volts to the input volts V_k, i.e. for a longitudinal kicker

$$K_{\parallel} = \frac{(\Delta E/e)}{V_k} \tag{3}$$

where e is the electronic charge, and for a transverse kicker the kicker constant is

$$K_{\perp} = \frac{\Delta p_{\perp} \beta c}{V_k e} \tag{4}$$

where $\Delta p_{\perp}$ is the transverse momentum change and βc the particle velocity.
(Since this definition does not exclude the use of a voltage transformer this ambiguity can be avoided by stating explicitly a 1:1 transformer or by considering the power flow and using the shunt impedance RT^2. The value of K can also be usefully expressed per meter of kicker tank.)

By applying the reciprocity theorem Lambertson [1] shows the relation between pickup and kicker criteria to be

longitudinal
$$Z_{\parallel} = \frac{Z_c}{2} K_{\parallel} \tag{5}$$

and transverse
$$Z_{\perp} = -j\left(\frac{Z_c \omega}{2\beta c}\right) K_{\perp} \tag{6}$$

where Z_c is the characteristic impedance at the signal port.

In other terms, if we can for example measure the transfer impedance of a pickup we can obtain its potential performance as a kicker.

To give an idea of orders of magnitude, one finds in the literature values of transfer impedance between say 50 Ω and several hundred ohms for longitudinal pickups. For 50 Ω circuits the corresponding longitudinal kicker constants then should be of the order of 2 to 10 eV per volt.

Exercise for the student. The reciprocity theorem states that the positions of an impedance-less generator and ammeter in a network can be interchanged without affecting the ammeter reading. Find a formal statement of this which can be applied to this case of an external voltage and resulting fields, and an internal current density and a resulting output voltage, and use this to derive Eqs. (5) and (6) from the pickup and kicker expressions above.

3.2 Bandwidth and balance

A second criterion is the degree to which a structure maintains its quality over the working frequency bandwidth [3], which, in the microwave region, is often an octave. This requires work on prototypes in order to make the most of the inherent bandwidth of the design, and so that any unwanted waveguide type resonances in the structure and its surroundings can be dealt with; then measurements of reflection coefficient and transmission loss carried out at the terminals may reveal multiple reflections from insulating supports, etc. and from vacuum feedthroughs once the structure has been installed in its vacuum tank. In the past decade the techniques of measurement of transfer impedance by means of wires or coaxial lines simulating the beam have progressed considerably, and these tests of beam plus structure over the working band are proving very valuable.

We can also include in our quality requirements a high degree of electrical balance (a low common-mode component) in the structure and in the associated summing and differencing circuits (see Section 4.4 below). When, in addition, an accelerator is being set up say for maximum effective aperture, or optimum working point in the lattice, it does not necessarily follow that the beam will pass through the center of the pickup, and it is therefore useful to make the structure adjustable in position [4].

3.3 Beam coupling impedance

An important requirement of a pickup or kicker structure in an accelerator is that the structure should be practically invisible to the beam. When the wall of the beam tube is made irregular, the image currents can accumulate at discontinuities and radiate high-frequency fields, which can interact with the beam and be destructive at high intensities. These effects are summarized by the *beam coupling impedance*, which can be determined experimentally by a differential measurement [5, 6]. The impedance of a central wire in a smooth beam pipe as reference is measured and stored as the calibration and then the irregular beam pipe is measured, which yields the complex impedance contribution of the irregularity. The method loses validity when several irregularities are coupled by the measuring wire.

In the mechanical design of pickups and kickers, and the accelerator vacuum chamber in general, care is taken to keep departures from a smooth beam tube to a minimum, and hence to keep the coupling impedance and potential interaction with the beam to a minimum. Other effects to be avoided are resonances excited at an abrupt change in cross section in a large diameter bellows section (for example in the CERN AA such resonances fell in the frequency range of an adjacent pickup and had to be suppressed by the insertion of damping resistors).

3.4 Operational requirements

A practical requirement is that the dimensions and the high-frequency properties of dielectrics and electrical contacts should be thermally reversible, i.e. should return to their original values after a vacuum bakeout cycle has been applied and some mechanical 'working' has occurred.

In terms of reducing down-time for fault correction, it can obviously be useful if operational requirements are considered during the design and development stage, for example by building in system checks from the control room, making full use of the capabilities of modern instruments -calibration etc.-, and by incorporating measurement ports in structures, enabling one quickly to check transmissions, and so to eliminate one set of uncertainties in the event of system malfunction.

4. PICKUP AND KICKER STRUCTURES

4.1 Wall current pickup

The passage of a particle beam along the axis of a metal tube requires, as in a TEM coaxial line, a wall current [2, 7-10] of the same magnitude as the beam but in the opposite direction,

$$-i_w = i_b$$

to satisfy the continuity equation statement

$$\frac{-dI}{dx} = \frac{ds}{dt}$$

where s is the surface charge density. This remains true at all of the frequencies belonging to a circulating beam and arising from its time structure, assuming TEM propagation and particle velocity $v \rightarrow c$, but is no longer valid above frequencies where non-TEM propagation begins. The detection of these wall currents is done in *image current* devices, as distinct from the *image line* or slow-wave structures which are described later.

If the vacuum chamber tube is interrupted by a short gap as in Fig. 1, to form a short outer coaxial line which can be terminated in its characteristic impedance Z to avoid resonances, the gap capacitance will be shunted by Z and by the resistance R of a measuring circuit, so that the equivalent circuit shows a constant current generator i_b driving C, Z and R in parallel, Fig. 2. A constant current can be assumed at high γ values where the particle energy is changed negligibly by passing the gap.

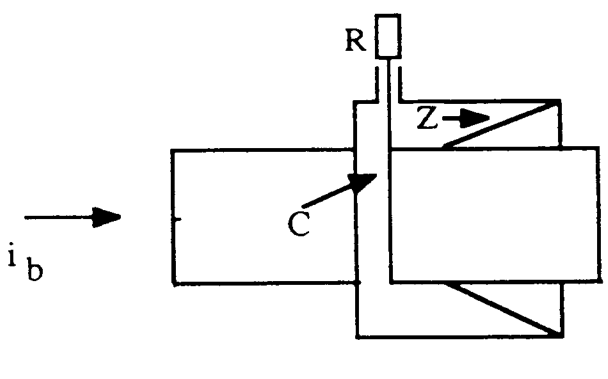

Fig. 1 Single gap

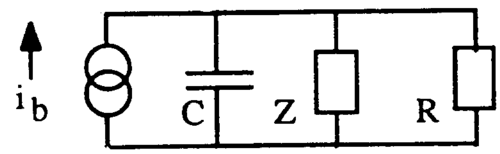

Fig. 2 Equivalent circuit

The transfer impedance, the ratio of measured voltage to beam current is then

$$\frac{V}{i_b} = \frac{1}{j\omega C + (1/Z) + (1/R)} = \frac{RZ}{R + Z + j\omega CRZ} \quad . \tag{7}$$

In the CERN SPS version from 1978 [7], there are eight 50 Ω strip-line outputs spaced around the pickup leading to vacuum feedthoughs and an external circuit which combines them into one 50 Ω output. The image current is shared between these eight lines and the terminated 25 Ω outer coaxial shielding line. This arrangement reduces the real component at the gap to 5 Ω, and the RC time constant accordingly, in the interests of high-frequency response but at the expense of transfer impedance. This 5 Ω is the equivalent of ten 50 Ω lines in parallel, so the power transferred by each to the final 50 Ω output is $(i_b/10)^2\,50$, and the total is $10(i_b/10)^2 50$, which is equated to $V_0^2/50$ to obtain the transfer impedance or sensitivity V_0/i_b = 15.8 Ω, for a lossless combiner network.

The pickup is useful between 4 MHz and 4 GHz, is simple, and has done sterling service.

4.2 Directional couplers

When two gaps are made in the beam tube of the previous section (4.1) the gaps can be made to share a common outer coaxial and produce two outputs [2]. It can be shown that the distance between the gaps, which represents a beam transit time and a phase difference for any given frequency, will result in output signals which can be chosen to be a maximum for one beam direction and a minimum for the other. With a length of a quarter wavelength, the signal is a maximum at the upstream end [1, 2, 8, 11].

The physical form of such 'directional couplers' varies greatly. They can be gaps as described, or loops entering the beam tube at one point and following the inner wall for a quarter wavelength before leaving through another, or similar loops short-circuited or terminated at one end, or the equivalent in microstrip. The transfer impedance of directional couplers is high relative to other methods over an octave bandwidth, and the usable frequency has increased steadily over the years [12-20].

It can be shown [2] that with a particle velocity v_p, wave velocity v_ϕ along the loop of length ℓ, frequency ω, load resistor R_0 and for the condition $v = v_p = v_\phi$, the sensitivity S can be written

$$S = \frac{R_0}{2}\left(1 - e^{-2j\omega\ell/v}\right) \tag{8}$$

and the signal appears only at the upstream end with maxima for $\ell = \lambda/4$, $3\lambda/4$, $5\lambda/4$ etc., the corresponding time-domain response being two delta spikes of opposite sign separated in time by $2\ell/c$, i.e the travelling time to the end of the loop and back. The output powers are usually added in combiner circuits so that for n loops the voltage sum increases with $n^{1/2}$. In the search for yet higher sensitivity one can join groups of loops together in series to achieve local increases with n, but then there is a trade-off with frequency response which falls away with sinf/f centered around $\ell = \lambda/4$.

The sensitivity is an important factor, but for the detection of very small beam intensities from a proton-to-antiproton target for example, the reduction of the noise level has to be worked on as well.

In the CERN ACOL project [16], in which a second collecting ring was built around the existing AA to increase the stacking rate, the pickup loops and structure are cooled down to 20 K, surrounded by a 50 K heat shield, and the preamplifier and load cold-box which is outside this system (both ends of the loops are taken out of the structure to the preamplifiers and terminations), are down to 18 K [21]. To complicate matters the pickup structure has to follow the beam diameter in as it is cooled (to maximize the signal), while preserving symmetry around the beam. The loop girders move between ferrite-loaded walls. The total heat losses from the cooled structure through the supports, plunging tubes, flexible strip line and radiation are of the order of 5 watts.

In Fig. 3 below we see the end view of an open ACOL pickup tank, and one can discern the upper and lower rows of loops at the center of the photo and the adjacent ferrite-loaded sidewalls, and above and below the loops the combiner board and coaxial line trays, and the movable strip-line connections to the fixed outer structure, with the whole enclosed within the heat shield.

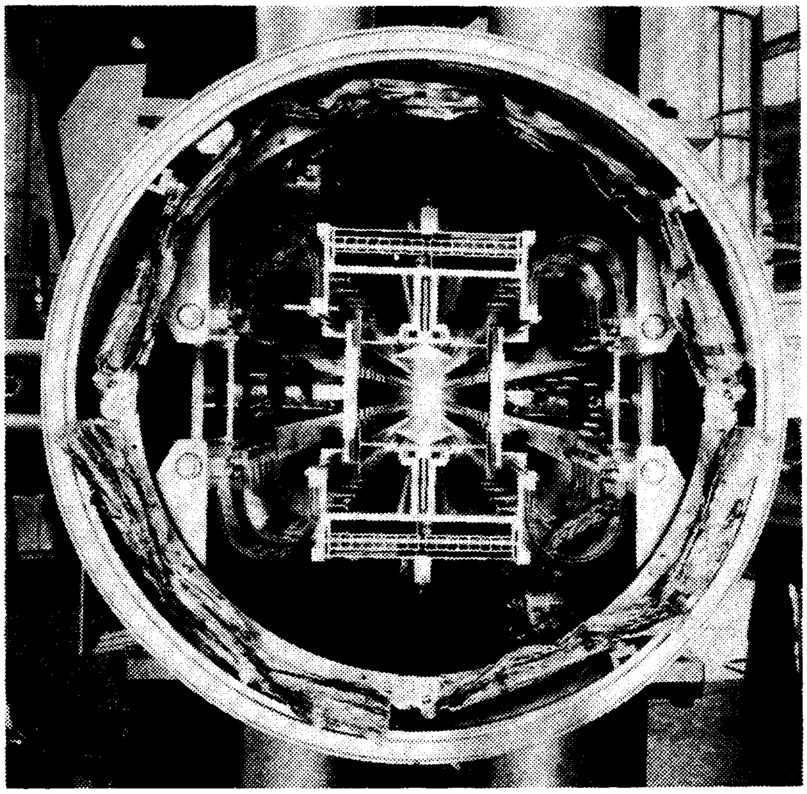

Fig. 3 End view of an ACOL pickup tank

Figure 4 shows an exploded view of a pickup. Of particular interest is the combiner board system, whose job is to combine the outputs from loop pairs into a common output with the contributions from each loop pair in phase. The construction, of printed circuit on alumina sheet using CAD, exhibited some dispersion, but with some adjustments and addition of lossy material and ferrite at strategic points, the effects of dispersion were kept down to <10° of phase.

The ACOL kickers are similar in concept to the pickups, but require circulating cooling water to take away the heat (order of 100 watts) in place of the refrigerating systems.

The Fermilab p^- has faced similar challenges with the upgrading of the accumulator core cooling to 4-8 GHz loops [4,19].

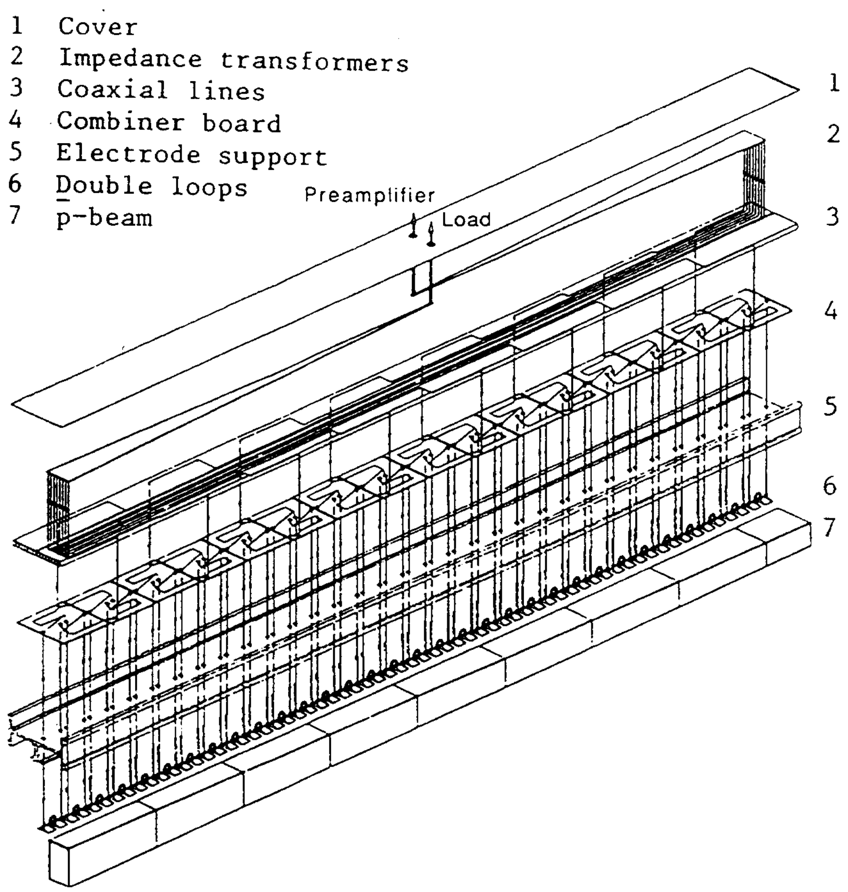

Fig. 4 Exploded view of an ACOL pickup

In both laboratories designers have looked at the 3-dimensional complexities of the individually fitted loops and have thought about getting the coupling elements into 2-dimensions for ease of production by printed circuit techniques, and these propositions will be discussed further under "slot lines" below.

Electron machines can also be big users of directional couplers or 'thin-wire pickups' as beam position monitors (BPM's). For example the Continuous Electron Beam Accelerator Facility CEBAF will need between 400 and 600 BPM's working with a center frequency of 1.5 GHz [13].

Loop couplers have provided the backbone of stochastic cooling throughout its short history, and for much longer, more generally, for beam monitoring.

4.3 Resonant Cavity

Resonant cavities have been the standard method of accelerating particles since the time when experimenters sought energies higher than those available from high-voltage generators in the early 1930's, and they had been proposed even earlier [22]. In this sense, therefore, longitudinal rf kickers were born with resonant particle accelerators as we know them today.

Most of the kickers which we discuss in this paper work by applying a deflecting field which travels with the particles either effectively by the timing of delays in a splitter, or physically along a transmission line. The pickups work the same way but in reverse.

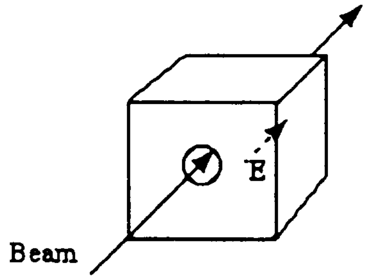

Fig. 5 Resonant cavity kicker

A resonant cavity, however, supports standing waves by multiple reflections, and for this case of a time-varying e/m field it can be shown [1] that a longitudinal electric field is a necessary condition for either longitudinal or transverse deflections. Reference [1] also derives the expressions for the shunt impedance longitudinally and transversely as functions of the Q-factors. This reminds us that the use of resonant cavities is limited to a narrow band of width $\Delta f = f_0/Q$. When resonant cavities are combined together as cells in a longer structure they can be used as standing wave devices in which the particle sees a travelling wave, as for example in a proton Linac, or as travelling wave devices as in the CERN SPS accelerating cavities.

Exercise

In a previous lecture [23] we heard of the 400-odd different types of cyclotron cavities in use around the world. It should be pointed out that not far from the room in which these lectures were presented there are some 1500 resonators, each different from the others, and each with a carefully adjusted fundamental frequency and frequency spectrum. They are installed in groups sharing similar spectra.

Each resonator is locked by tight coupling to a drive unit, and the dc power and coupling are adjusted for each 'driver-resonator' combination to produce the *fundamental, spectral distribution* and *frequency stability* required.

Where are they?

(Answer: In the organ of the College Chapel)

4.4 Faltin slot structures

If we fix a rectangular coaxial line parallel to a beam tube and cut slots in the common wall, transversely to the beam direction as in Fig.6, we see that the particle fields can be coupled with the inner of the coaxial line at each passage past a slot, and can propagate along the line with a degree of synchronism with the particle velocity which depends upon the dispersion produced in the coaxial line by the presence of the slots. As we increase the slot size and coupling, we increase the signal collected from each slot, but impair the coherent accumulation of signals at the end of the line as they fall out of synchronism, and we can also lose more energy by re-radiation back into the beam chamber.

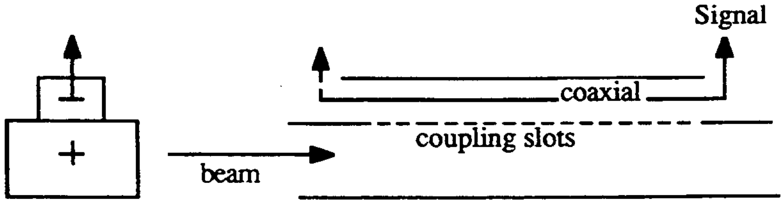

Fig. 6 Faltin slot structure

These phenomena put an upper limit to the coupling and to the transfer impedance of the device [24-27], but with a high-beam intensity as in a storage ring one can afford to work with low coupling and benefit from the good wideband response of the structure associated with near-synchronism. A high-frequency limit is approached when the slot long dimension approaches a half-wavelength and the coupling becomes very strong.

As pickups the structures have the feature of signal amplitudes proportional to frequency both for longitudinal and transverse particle motion, while as kickers they give kicks constant with frequency in the transverse mode but again proportional to frequency in the longitudinal mode.

These structures were proposed, analyzed and developed at CERN by Faltin [24] in the 70's for the ISR stochastic cooling experiments in the 1-2 GHz band, and were later adapted to the requirements of the stack-core cooling system of the Antiproton Accumulator ring (AA) using the same 1-2 GHz frequency band, and then further extended to 2-4 and 4-8 GHz for the ACOL project [28] which was aimed at increased stacking rates, intensities and collider luminosities. The slot structure dimensions could be simply scaled with wavelength for the higher frequencies of ACOL, but the structures and tanks were largely redesigned mechanically to avoid the coaxial runs in vacuum which were difficult to assemble in the original 1-2 GHz design, and with the smaller dimensions it became possible to integrate the input and output lines into the structures.

In the AA design [29], for the 1-2 GHz longitudinal cooling kicker it was assumed for the computer optimization of cooling parameters that the kicker constant, the ratio of the voltage seen by the particle to the voltage applied to the kicker, was three (this was a conservative reduction from a calculated figure nearer five), which implies that the longitudinal sensitivity from Eq. (5) was 75 ohms.

A "slot-box" electrode is in essence a 2-port device, with both ports taken through the vacuum if it is wished to check its transmission and reflection while it is in place in the ring, and with an external matched load connected to the upstream port to absorb the backwards wave from the slots in normal operation. Alternatively the upstream port can be terminated by a matched load in the vacuum, thus avoiding the complication of imperfectly matched vacuum feedthroughs, but losing the ability to check the structure without opening up the vacuum.

Fig. 7 below shows the transmission plot of a 4-8 GHz slot box on a 1dB/div. scale.

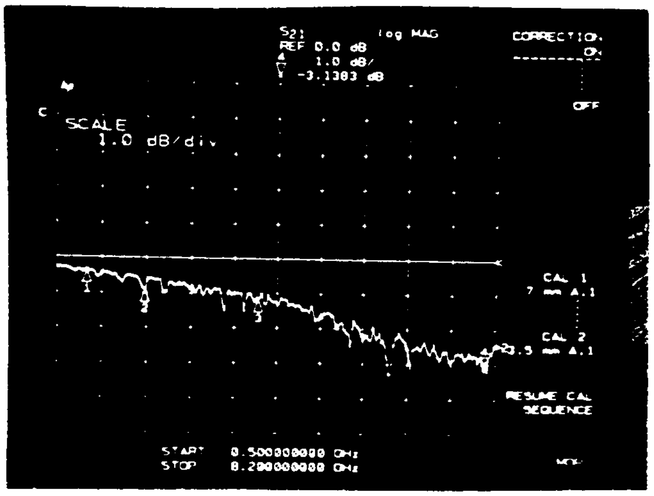

Fig. 7 Transmission of a 4-8 GHz slot box

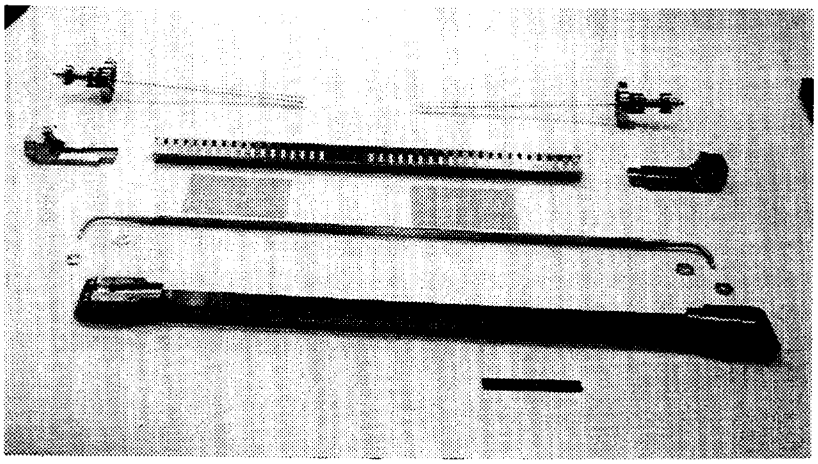

Fig. 9 4-8 GHz slot-box details

Exercise

Plot a graph of the ratio between the Σ and Δ for varying ratios in dB between the signals.

4.5 Slot lines

The *slot-line* structure adapts the techniques of microstrip to produce slots, transverse to the beam direction, by the periodic interruption of the conducting layer on a continuous dielectric substratum Fig. 10. However, instead of coupling the particle fields to a secondary coaxial line these slots produce individual output currents via microstrips leading to a combiner board. A physical picture in accordance with the analysis [33] is of an image current proper to a beam particle arriving at the center of the transverse slot, splitting in two, and propagating outwards and transversely to the ends, to an output and to a termination. This introduces a transverse transit time dimension.

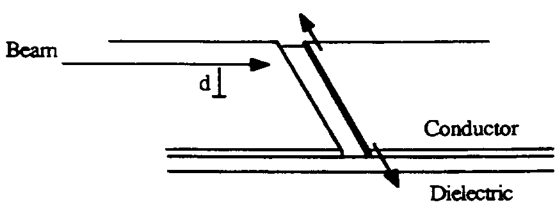

Fig. 10 Slot-line principle

Although the techniques of slot lines were known and described in the 70's, it appears that the first proposal to apply them to beam pickups and kickers was made in CERN in 1985 [30-32]. In the same year an analysis of their performance also appeared [33]. Since then reports have also appeared on studies carried out at the Fermilab, including a proposal to combine the slot lines with co-planar quarter-wave loops as well as to use slot lines in their own right [19,20,33].

In Ref. [33] we find derivations of the sensitivity for one slot and for the difference mode, the sensitivity for one slot being

$$S = 0.5\sqrt{R_0 Z}\, e^{-2\pi d/\lambda} \quad . \tag{9}$$

The variations across the band are not serious in terms of loss of signal at the output port, but when the signal is subtracted from that of the opposite electrode at a given frequency the result can be misleading information sent to the kicker in a cooling system, and slower cooling. This was of particular importance in the ACOL where a former 1-2 GHz stack-core kicker became the stack-tail kicker which was to be fed with the order of 100 watts [16], and in order to limit transverse heating we needed the unbalance between opposite slot boxes to be very small from 1 to 1.6 GHz, with the ratio between the unwanted transverse heating and the wanted longitudinal kicks to be less than -30dB. This was measured by storing the two transmission data and using the instrument's sum and difference options to show the ratio between their values (Fig. 8).

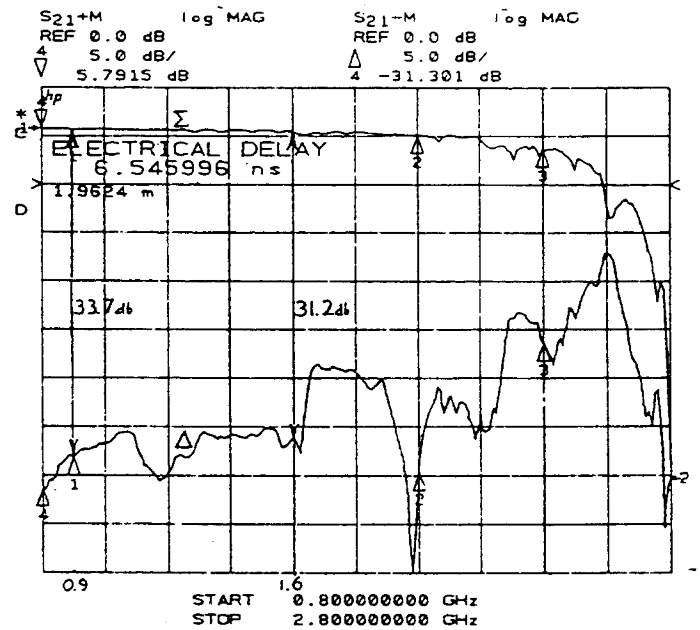

Fig. 8 Network analyzer Σ and Δ plots of 1-2 GHz slot boxes

The summing and differencing of the signals from pairs of slot-box electrodes is done with commercial hybrids. This draws our attention to a major difference between this and the previous structures discussed, in that the combining of signals from different slot elements is inherent in the structure, so that there is only one available output per electrode, with no need for combiner boards. The problem of reproducibility between many coupling elements is confined to the machining of slots, which can be very accurate, and to the flatness of the slot masques or plates, which was somewhat compromised, however, in the AA 1-2 GHz electrodes by a desire to have them easily removable for changing the coupling should this be necessary. The slot masques were pressed up against the top of a groove by spring fingers which needed some care to adjust.

An attractive feature of the structures from the vacuum point of view is that they can be constructed almost entirely of metal, except for small pieces of insulating material supporting the coax inners, which produce little outgassing. These were made of a machinable ceramic in the 1-2GHz boxes, and Vespel and ceramic pins respectively in the 2-4 and 4-8 GHz structures.

Figure 9 shows the interior details of a 4-8 GHz slot box which is screwed together to avoid the contact spring problem.

where R_0 is the output impedance, Z the slotline impedance with perfect matching to R_0, λ the wavelength along the slot, and d the beam distance from the slot. With d «λ (9) simplifies to

$$S = 0.5\sqrt{R_0 Z} \quad . \tag{10}$$

For two slots in the difference mode separated by h, and with the beam close to the pickup center the sensitivities become

$$S = 0.5\sqrt{R_0 Z}(\pi/\lambda)(1/\sinh(\pi h / 2)) \tag{11}$$

and for a small gap h « λ

$$S = (1/h)\sqrt{R_0 Z} \quad . \tag{12}$$

In contrast to these matched or travelling wave examples, standing wave slot lines are expected to deliver more signal but over a narrower frequency band [31].

Transfer impedance measurements of standing wave slot lines show similar responses to $\lambda/4$ loops both with simulated beam and electron beam measurements [19, 31]. The standing wave realizations could in fact be more sensitive than the loops but fall off faster as the beam departs from the slot center.

Comparative tests between normal directional coupler loops, planar loops and slots have been carried out at Fermilab [19], leading to the conclusions that planar loops are similar in performance to normal loops but easier to manufacture. The $\lambda/2$ resonant slot lines were found to out-perform loops in some respects and have an important advantage in the closer spacing permitted ($\lambda/4$ rather than $\lambda/2$ for loops), and therefore can produce more pickup signal per straight-section length.

4.6 Slow wave structures

The Faltin slot structure represents a "small-lumped" approximation to continuous coupling to a beam, but it can be seen to be ultimately limited in coupling by the dispersion on the coupling line and higher modes [34] or power loss back into the beam chamber. There is therefore some interest in any method which approaches more closely a continuous low dispersion medium to couple the particle fields synchronously to the propagation on an output line.

In 1962 the late E. Jones proposed a device which would employ the principle of Cerenkov radiation to detect charged particle beams [35], following a 1955 analysis by Danos for the case of bunched electron beams [36], and in the 1980's this was looked at again in the CERN PS AA group and some models were built and tested. L. Faltin and E. Brambilla published the results of their independent studies for the AA in 1985 [34,37], and in 1987 E. Brambilla followed with the results of experimental work [38]. Others elsewhere had been thinking along similar lines, with a paper on a dielectric synchronous wave pickup by G. di Massa and V.G. Vaccaro in Naples in 1984 [39], and from 1985 onwards the CERN SPS Division and a CERN/Naples University collaboration published in CERN their work on synchronous wave structures [41-43].

The general problem is to slow down the phase velocity in the pickup element to match the particle velocity, which is less than but close to c. A beam chamber reacts to particle fields as do waveguides, where the phase velocity in general is greater than c, but two ways of slowing down the wave velocity have been investigated, dielectric slabs and corrugated walls. In either method one has to solve the field equations in the modified waveguide and then to solve the design problem of matching its output to a system characteristic impedance.

The physical mechanism in the dieletric slab is of waves skimming along the beam-side surface of the dielectric and producing angled wave fronts in the dielectric and propagation by total internal reflection, with an angle θ in the dielectric given by $\cos\theta > 1/n$; this fulfills the Cerenkov radiation condition which requires $\cos\theta = 1/\beta_p n$. Here n is the refractive index of the dielectric material, related to ε_r the relative permittivity by $n = \sqrt{\varepsilon_r}$, and β_p is the particle velocity ratio v_p/c. As the particle moves forward, constructive interference occurs at those wave fronts where the wave phase velocity equals the particle velocity.

The phenomenon was studied by Faltin [34] for rectangular dielectric slabs centered against the upper and lower walls of the beam chamber, Fig. 11, and he concluded from analysis and performance calculations that the "image-line" coupler had a higher coupling per unit length than the slot coupler, but was similarly limited in bandwidth (probably an octave) by dispersion and higher modes etc., there remaining still the advantage of higher frequency operation due to its non-lumped structure.

The Brambilla study [37, 38, 43] used shaped dielectrics continuous with the upper and lower walls to aid the matching into 50 ohm outputs (Fig. 11), and showed that the coupling with the synchronous mode took place as predicted, but that the response as a pickup was lower than predicted as was the bandwidth, possibly since the interaction length was too short to depress an unwanted fast mode.

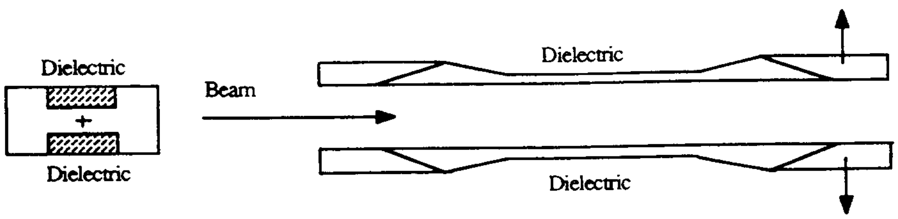

Fig. 11 The Faltin (left) and Brambilla (right) image line models

Another approach to the dielectric pickup by Boussard and di Massa at the SPS [42], as a move in the direction of slow-wave structures, reported quite good agreement between theory and measurement and at the interesting frequency of 10 GHz. This paper also described a good measure of agreement for a corrugated waveguide.

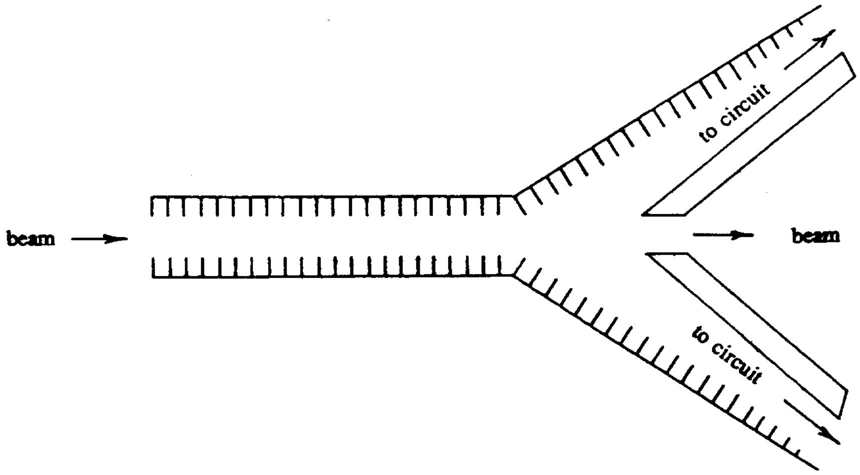

Fig. 12 Corrugated waveguide slow wave structure

The corrugated wall waveguide may be thought of as slowing down the phase velocity by a closely spaced set of susceptances or irises at the chamber walls (Fig. 12). A corrugated wall transverse pickup designed for 10 GHz has been shown analytically and experimentally to result in linear regions in the dispersion curves with $v_p < c$ [42]. One notes the affinity of these multi-cell structures with the transverse mode rf beam separator and with the longitudinal acceleration of the travelling wave electron linac.

Both the dielectric and corrugated apertures studied were modest, but the results were convincing demonstrations of principle for slow wave structures.

5. CONCLUSIONS

There has been lively activity in the development of microwave pickups and kickers for particle accelerators in the past decade, mainly in response to the needs of stochastic cooling and of pp^- colliders. Higher frequencies and bandwidths with high sensitivities remain desirable aims for continuing development, to allow faster stacking rates and higher intensities and collider luminosities, and event rates at the end. Dielectric couplers and corrugated waveguide structures have given some promise of continuous or near-continuous, synchronous coupling of particle fields to structure fields over a large frequency band, but have yet to enter the competition with adequately large apertures.

BIBLIOGRAPHY

[1] G. Lambertson, Dynamic Devices - Pickups and Kickers, AIP Conference Proceedings No. 153, Vol. 2 (1985), pp. 1414-1442.

[2] D. Boussard, Schottky noise and beam transfer function diagnostics, CERN Accelerator School, Oxford, 1985, CERN 87-03 (1987).

[3] S. van der Meer, An introduction to stochastic cooling, Lecture given at the Summer School on High-Energy Particle Accelerators, Fermilab (1984), AIP Conf. Proc. (1984).

[4] J. Petter, D. McGinnis, J. Marriner, and J. Misek, New 4-8 GHz core cooling pickups and kickers for the Fermilab accumulator, IEEE Proc. Part. Acc. Conf. 1989, pp. 648-650.

[5] F. Caspers, Beam impedance measurement by the wire method using a synthetic pulse technique, In: Proc. of the Particle Accelerator Conf., Vancouver (1985), CERN/PS/85-44 (AA) (1985).

[6] F. Caspers, Beam impedance measurements using the coaxial wire method, Workshop on Impedances and Current Limitations, ESRF-Grenoble (1988), CERN PS/88-59 (AR-OP) (1988).

[7] T. Linnecar, The high-frequency longitudinal transverse pickups used in the SPS, CERN-SPS/ARF/78-17 (1978).

[8] J. Borer and R. Jung, Diagnostics, CERN Accelerator School, CERN, Geneva, 1983, CERN 84-15 (1984).

[9] G.C. Schneider, A 1.5 GHz Wide-band beam-position-and intensity monitor for the electron-positron accumulator (EPA), CERN/PS 87-9 (BT), (1987).

[10] T.J. Fessenden, B.W. Stalland, and G.G. Berg, Beam current and position monitors for the Astron Accelerator, Rev. Sci. Instrum., Vol. 43, No. 12 (1972), pp. 1789-1792.

[11] R.E. Shafer, Characteristics of directional coupler beam position monitors, IEEE Trans. Nucl. Sci., NS-32, No. 5 (1985), pp. 1933-1937.

[12] D. McGinnis, J. Petter, J. Marriner, J. Misek, and S.Y. Hsueh, Frequency response of 4-8 GHz stochastic cooling electrodes, IEEE Proc. Part. Acc. Conf. 1989, pp. 639-641.

[13] W. Barry, A general analysis of thin wire pickups for high frequency beam position monitors, CEBAF PR-90-024 (1990).

[14] F. Völker, T. Henderson, J. Johnson, An array of 1- to 2-GHz electrodes for stochastic cooling, IEEE Trans. Nucl. Sci., NS-30, No.4 (1983).

[15] R.L. Carlson and L.E. Stout, A multigigaherz beam-current and position monitor, IEEE Trans. Nucl. Sci., NS- 32, No.5 (1985).

[16] B. Autin, G. Carron, F. Caspers, S. Milner, L. Thorndahl, and S. van der Meer, ACOL stochastic cooling systems, 1987 IEEE Particle Accelerator Conf., Washington, D.C. (1987), pp. 1549-1551.

[17] B. Autin, G. Carron, F. Caspers, and L. Thorndahl, Applications of Microwaves to Antiproton Control, 17th European Microwave Conf., Rome (1987), Alta Frequenza, Vol. LVI-N.10 (1987).

[18] J. Marriner, Stochastic cooling at Fermilab, XIIIth Internat. Conf. on High-Energy Accelerators, Novosibirsk, USSR, (1988).

[19] J. Petter, D. McGinnis, and J. Marriner, Novel stochastic cooling pickups/kickers, IEEE Proc. Part. Acc. Conf. 1989, pp. 636-638.

[20] D.P. McGinnis, Theory and design of microwave planar electrodes for stochastic cooling of particle beams, Special Issue Microwave and Optical Technology Letters, to be published October 1991.

[21 P. Lebrun, S. Milner and A. Poncet, Cryogenic design of the stochastic pick-ups for the CERN Antiproton Collector (ACOL), Advances in Cryogenic Engineering, Vol. 31 (1986).

[22] G. Ising, The Principle of a method for the production of canal rays of high voltage, No. 7, The Development of High Energy Accelerators, (Ed. M. Stanley Livingston, Dover 1966.)

[23] C. Pagani, Cyclotron cavities, this School.

[24] L. Faltin, Slot-type pickup and kicker for stochastic beam cooling, Nucl. Instrum. and Methods, 148 (1978), pp. 449-455

[25] G.R. Lambertson, K.J. Kim, and F.V. Völker, The slotted coax as a beam electrode, IEEE Trans. Nucl. Sci., NS-30, No.4, (1983).

[26] J.D. Simpson, S.L. Kramer, D. Suddeth, and R. Konecny, Slot coupled beam signal development at Argonne National Laboratory, IEEE Trans. Nucl. Sci., NS-30, No.4, (1983).

[27] Fermilab Workshop on pickups, kickers and signal suppression, Fermi National Accelerator Laboratory, Batavia, Ill. (1982).

[28] J. Bosser, P. Bramham, C. Metzger, and C. Taylor, Design and performance of the AAC stack core cooling system, 1st European Particle Accelerator Conf., Rome 1988, CERN PS/88-25 (AR) (1988).

[29] S. van der Meer, Stochastic stacking in the Antiproton Accumulator, CERN PS/AA/78-22, (1978).

[30] F. Caspers, A broadband slot-line pickup, PS/AA/ACOL Note 32 (1985).

[31] F. Caspers, Planar slot-line pickups and kickers for stochastic cooling, CERN/PS/85-48 (AA) (June-August 1986), IEEE Trans. Nucl. Sci., NS-34 (1987), pp. 1866-1868.

[32] D. Boussard, Evaluation of slot-line pickup sensitivity, SPS/ARF Note 85-9 (1985).

[33] F. Caspers, Recent developments in stochastic cooling, 3rd European Particle Conf., EPAC 90, CERN PS/90-39 (OP) (1990).

[34] L. Faltin, Image line pickups and kickers for stochastic cooling, Nucl. Instrum. and Methods, A241 (1985), pp. 416-428.

[35] E. Jones, A proposal utilising Cerenkov radiation for the observation of longitudinal structure in relativistic particle beams, AR/Int.SR/62-5 (1962).

[36] M. Danos, Cerenkov radiation from extended electron beams, Journal of Applied Physics, Vol. 26, No. 1 (1955).

[37] E. Brambilla, A microwave Cerenkov pickup for stochastic cooling, CERN/PS/85-45 (AR) (1985).

[38] E. Brambilla, The AA Cerenkov microwave pickup prototype: experimental results and their interpretation, CERN PS/87-100 (AA) (1987).

[39] G. Di Massa and V.G. Vaccaro, Synchronous wave pickups for stochastic cooling in particle accelerators, Proc. 5a Riu di Elettromagnetismo Applicata, Saint Vincent, Italy (1984).

[40] R. James, Antiprotons in CERN, Industrial Training Report, Univ. of Bath, PS/AA/Note 85-12 (1985).

[41] G. di Massa, Synchronous wave transverse pickup, CERN SPS/ARF/Note 85-8 (1985).

[42] D. Boussard and G. Di Massa, High-frequency slow-wave pickups, CERN SPS/86-4 (ARF) (1986).

[42] D. Boussard, E. Innocente-Brambilla, and A. Jacob, On the measurement of the transfer impedance of a longitudinal pickup, SPS/ARF/Note 88-3 (1988).